NETEX TASK 1: A STUDY OF THE EFFECT OF ULTRAWIDEBAND (UWB) EMITTERS ON EXISTING NARROWBAND MILITARY RECEIVERS

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ABSTRACT

The goal of the Defense Advanced Research Projects Agency's (DARPA) Networking in Extreme Environments (NETEX) program is to create a wireless networking technology for the military user that enables robust connectivity in harsh environments and support its integration into new and emerging sensor and communication systems. Phase 1, which is now nearing completion, will result in a thorough understanding of the effects of Ultra-Wide Band (UWB) system operation on existing military spectrum users based on modeling, simulation, and measurements. In order to accomplish this task the DARPA Advanced Technology Office (ATO) procured UWB emitters and broadband antennas to use as interference sources and contracted with the Naval Air Warfare Center Aircraft Division (NAWC AD) Electromagnetic Environmental Effects (E^3) Division to provide candidate victim systems from the existing (legacy) US naval aircraft and shipboard inventory for testing. Testing was conducted on thirteen legacy systems during the period of October 2002 through March 2003. The purpose of this paper is to describe the results of these tests.

This paper will provide a brief discussion of the UWB emissions as described by the US Federal Communications Commission (FCC) and describe the generic UWB emitter used for these tests. It will then provide a brief overview of the general test plan and explain how it was adapted to the various systems tested. It will then provide a discussion of the results as they apply to the purpose of the NETEX program. Finally, the paper will look at where NETEX is going after Task 1.

INTRODUCTION

In the spring of 2002, the Defense Advanced Research Projects Agency's (DARPA) Advanced Technology Office (ATO) initiated the Networking in Extreme Environments

(NETEX) Program to create a wireless networking technology for the military user that enables robust connectivity in harsh environments and support its integration into new and emerging sensor and communication systems. Phase 1/Task 1, which is now nearing completion, will result in a thorough understanding of the effects of Ultra-Wide Band (UWB) system operation on existing military spectrum users based on modeling, simulation, and measurements. As part of this program, DARPA ATO contracted with the Naval Air Warfare Center Aircraft Division (NAWC AD) Electromagnetic Environmental Effects (E^3) Division to provide candidate victim systems from the existing (legacy) US naval aircraft and shipboard inventory for testing. These systems were subjected to conducted electromagnetic interference (EMI) testing similar to the tests of MIL-STD-462[1] procedure CS04 and MIL-STD-462D[2] and MIL-STD-461E[3] procedure CS104. The results of this investigation would provide the information necessary to evaluate the potential for UWB devices to interfere with existing military radio communication and sensing systems and help to understand how UWB systems could be implemented in a manner that makes optimum use of their unique capabilities.

The tests discussed in this paper were conducted at NAWC AD, Patuxent River and St. Inigoes, Maryland. The primary testers at NAWC AD were A. Light and E. McNett of SYColeman Corp., and T. Carney of Systems Planning Corporation. They were supported by numerous US Navy employees and contractors who are expert in the operation and maintenance of the various units under test (UUT). The testing was conducted during the period of October 2002 through March 2003.

In order to keep this report unclassified, the actual systems tested are not named. The DARPA NETEX Program will be publishing individual test reports for each system and an overall final report detailing the composite results.

DESCRIPTION OF UWB AND THE GENERIC UWB GENERATOR

What Are UWB Emissions?

The U.S. Federal Communications Commission (FCC) has defined a UWB device to be any intentional radiator of radio frequency (RF) energy, which has a 10 dB bandwidth of 25% of the strongest frequency within that 10 dB bandwidth or a 10 dB bandwidth of equal to or greater to 500 MHz.[4, 5] Because of these extremely large bandwidths, these devices do not conform to the usual U.S. frequency allocation table and associated Federal Regulations. Figure 1 shows the mask of the peak average radiated power from an approved unlicensed commercial UWB measured at a distance of 3 m form the UWB antenna. The FCC recognizes six (6) different classes of UWB, each of which has a different allowed emission limit as shown in Figure 1. The six classes are: vehicular radar systems (VRS), handheld devices, indoor devices, low frequency imaging systems (IS), medium frequency IS, and high frequency IS. Unlicensed UWB with radiations below 960 MHz are regulated under a different section of Part 15 of the FCC rules. In this frequency region, the emissions are measured with an EMI receiver using a quasi-peak detector; therefore, the limit for emissions at frequencies below 960 MHz is in dBm. This mask also assumes an isotropic receive antenna.

Typically the output power of UWBs is low enough to be authorized under the unlicensed device regulations of the National Telecommunications and Information Administration (NTIA) and the FCC. However, these bandwidths are so wide that, UWB devices usually also emit signals in bands that are used for other RF services operating in allocated and regulated frequency spectrum. Under FCC rules, unlicensed devices are only allowed to operate so long as they do not cause interference to licensed devices or devices otherwise permitted to use the frequency bands in which the unlicensed devices operate. If the unlicensed device is found to cause interference, it is required to cease operation immediately.[5]

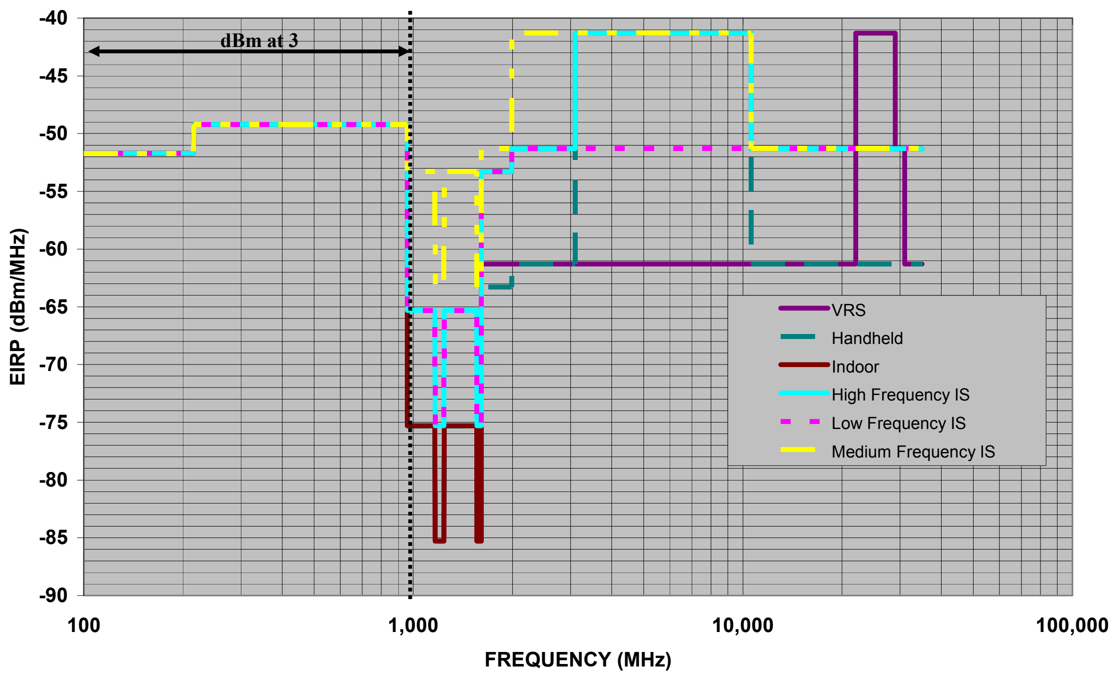

Figure 1 Peak Average Radiated UWB Power Measured at 3 m.

The NTIA and the FCC developed rules for unlicensed devices (conventional electronic devices with narrow bandwidths and very low total radiated power, usually with less than 1 W of peak output power) that did not address the then unknown UWB devices. Thus, the NTIA and the FCC must work closely with each other and the users they authorize, as well as with the UWB community to develop policies and procedures that will allow the UWB devices to work without interference to existing systems. The difficulty in measuring both the UWB signal characteristics and their effects on other devices exacerbates the difficulties of this coordination. The pulses are very narrow, often in the low nanosecond or picosecond range, requiring new measurement techniques and equipment to measure the signal characteristics accurately. Further, the interference effects of very narrow pulses and aggregations of similar pulses, such as could occur in some applications of UWB technology, are not well understood.

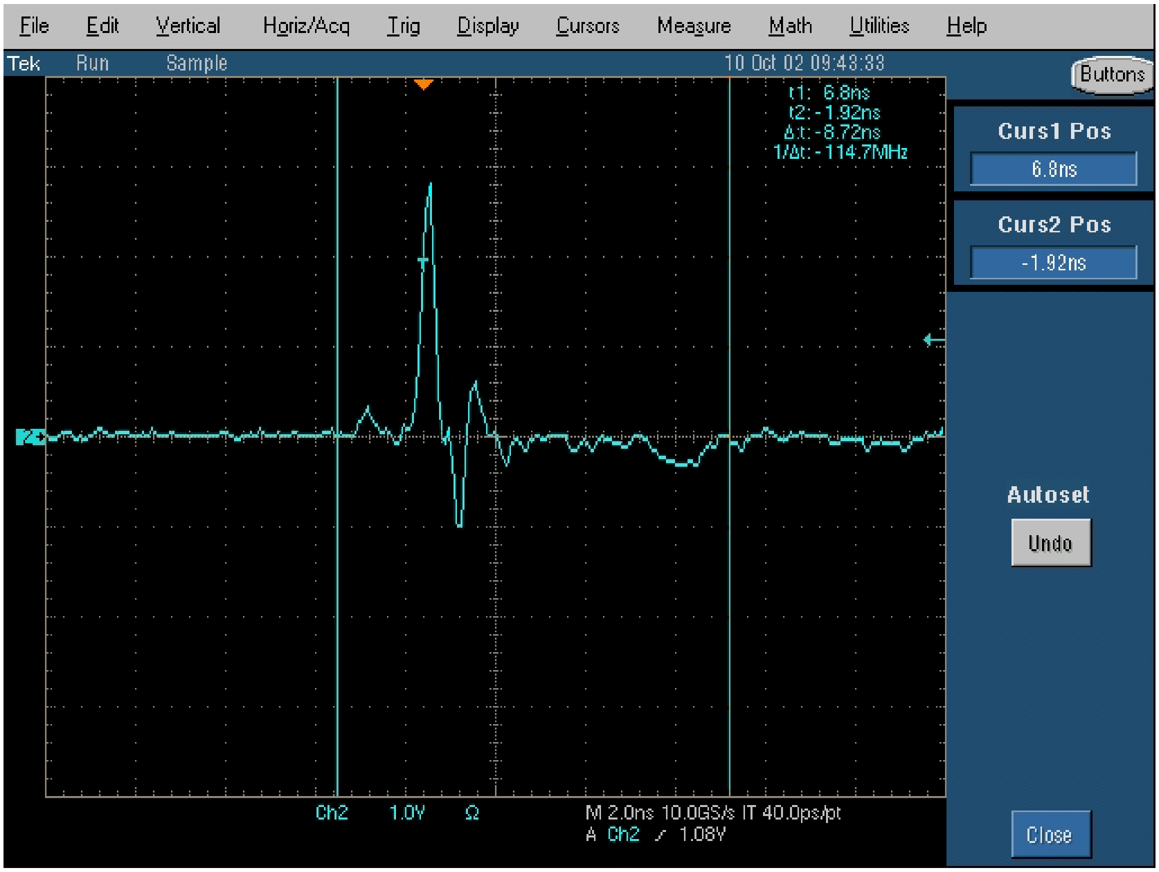

Figure 2 **Time Domain Representation of the Most Commonly Used Pulse from the Generic UWB Generator, the Positive Double Exponential (Pos DE) Pulse**

The Generic UWB Generator

The test program used a set of generic UWB generators designed to generate essentially the same pulse but over a large range of pulse repetition frequencies (PRFs) and pulse groupings to represent many different types of UWB generators considered to be operational today and in the near future. The peak output power of the generators was approximately 1 watt (W) with a frequency occupancy above -50 decibels (dB) with respect to the highest measurable frequency to be approximately 7 GHz. (For purposes of this paper, dB with respect to the highest measurable frequency would be abbreviated dBc.) Figure 2 shows a single pulse of the most commonly used UWB output pulse in the time domain. The test team designated this pulse as a positive double exponential (Pos DE) pulse because of its similarity to the classical electromagnetic pulse (EMP) and the initial lightning strike. Because the image was captured with a bandwidth limited oscilloscope, certain characteristics such as the peak voltage swings are not truly represented, but most of the pulse's characteristics can be determined from this image. This impulse is a classical high speed/short pulse "spark gap" emission. It is a noncoherent, carrierless emission, essentially incapable of providing "sub-clutter" processing gain, because individual pulses cannot be reconstructed out of the noise.

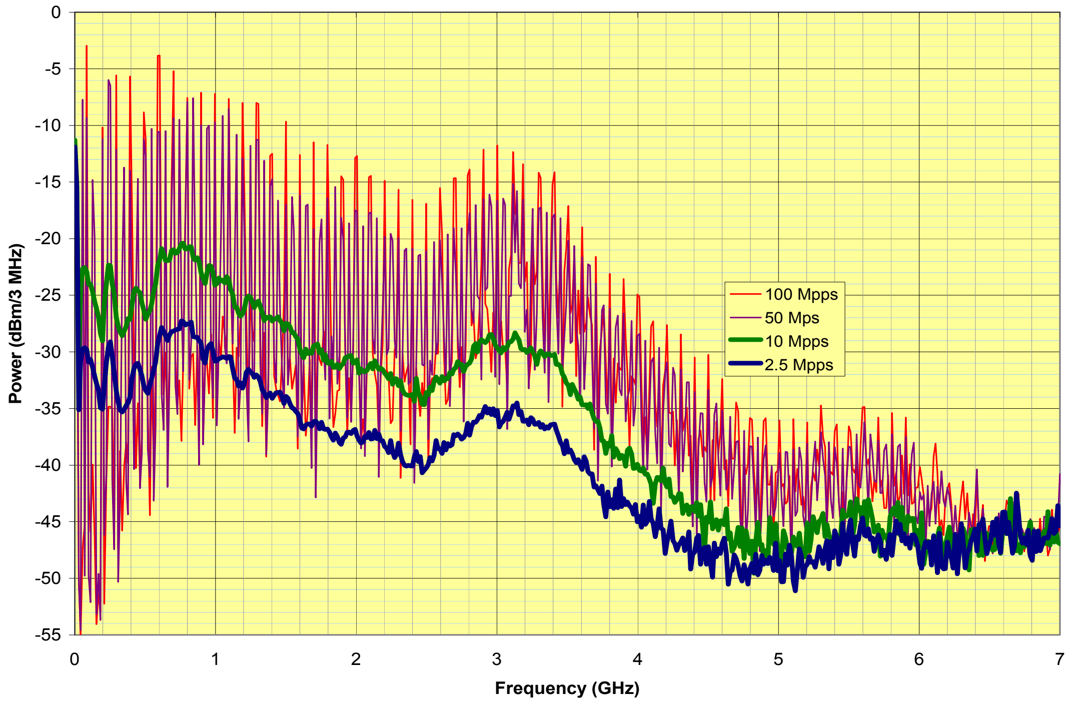

Figure 3 **Frequency Occupancy of the Positive Double Exponential Pulse for PRFs of 100 Mpps, 50 Mpps, 10 Mpps, and 2.5 Mpps**

Figure 3 shows the frequency occupancy of the UWB generators for a number of PRFs. The spectra in Figure 3 present the average power in a 3 MHz bandwidth for each sample window within the displayed frequency span, 7 GHz. Since the spectrum analyzer only stores 500 samples per scan, the image is under sampled, but provides the salient aspects of the spectra displayed. The UWB could also generate a negative double exponential (Neg DE), which was virtually a mirror image of the Pos DE.

The UWBs can be commanded to generate any fixed PRF between 1 pulse per second (pps) and 100 Mpps in increments of 1 pps. In addition PRFs of less than 80 Mpps can be dithered within limits defined in the UWB user's guide. Specifically, PRFs between 10 Mpps and 80 Mpps can only be dithered at a limited number of percentages (%), while PRFs at or below 10 Mpps can be dithered at any integral percentage between 1% and 100%. In addition to dithering the PRF can also be On-Off Keyed (OOK) in one (1) of twelve (12) patterns varying from a simple repetitive On-Off (1,0) pattern (Pseudonoise [PN] Factor 1) to a fully pseudorandom pattern of 12-bit numbers contained in a 4096-bit register (PN Factor 12). Other internal capabilities of the UWB generators, also described in the user's guide, were not used during these tests and are not described here. An unexpected feature of the generic UWB generator was its low stability internal oscillator. Although the instability was not noticeable at low harmonics of the desired PRF, at high harmonics the spectral lines began to display significant frequency sidelobes, as shown in Figure 4. At very high harmonics, these sidelobes begin to dominate the spectrum between spectral lines of the desired PRF, causing the spectrum to become completely noise-like, rather than discrete.

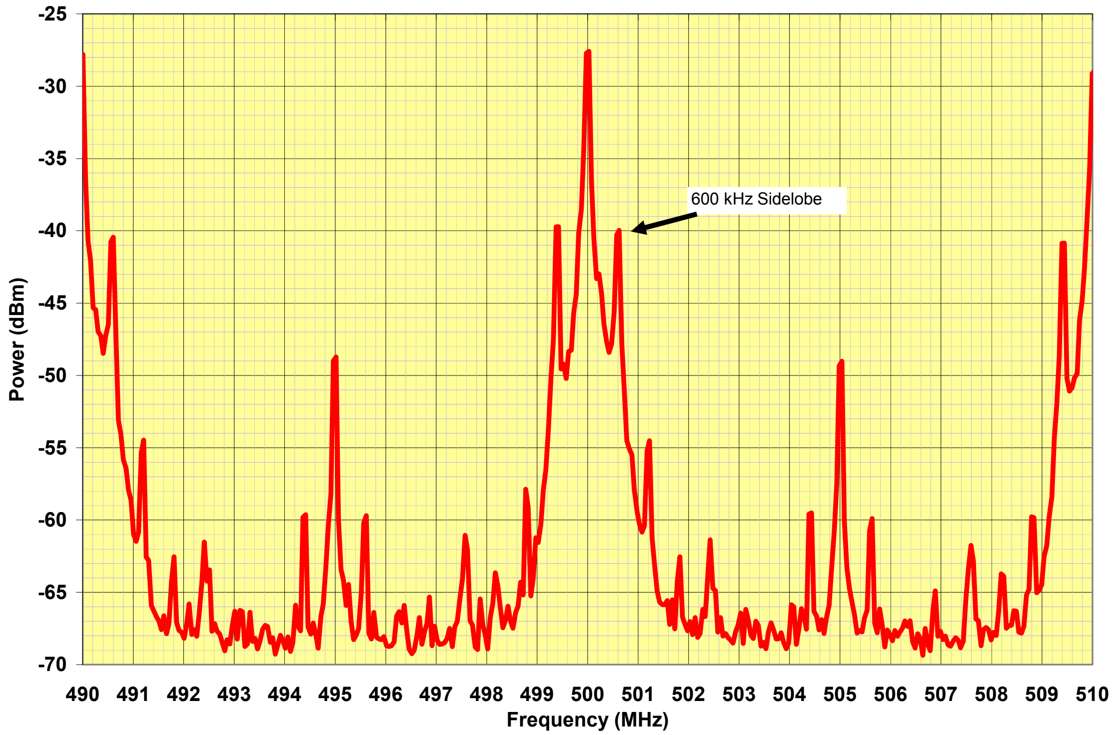

Figure 4 Sidelobes in UWB Clock Harmonics of 10 Mpps Pulse about Fiftieth Harmonic

In addition to the internally generated pulse waveforms, the UWBs would also accept an external modulation pulse with a PRF equal to or less than 100 Mpps for either the Pos DE or Neg DE. Because the external triggers for the Pos DE and the Neg DE were independent, a combination of Pos DE and Neg DE pulses could be generated to produce very specialized waveforms. The external generator pulses must pass through +3.5 V in the positive direction in order to cause the UWB to generate a pulse, for either the Pos De or the Neg DE.

In order to test potential victims with assigned frequency bands above 4 GHz, the test team used one or a combination of amplification techniques to produce sufficient UWB power. The primary amplifier was a commercial off-the-shelf (COTS) 1 – 26 GHz, 40 dB amplifier with a peak output power of about 1 W. The second amplifier was a proprietary electronic warfare (EW) traveling wave tube amplifier (TWTA) which was rated to operate across the band of 8 – 18 GHz, also with a peak output power of approximately 1 W. On occasion both of these amplifiers were used in series to produce a sufficiently strong test signal. The amplified output spectra of these devices are shown in Figure 5.

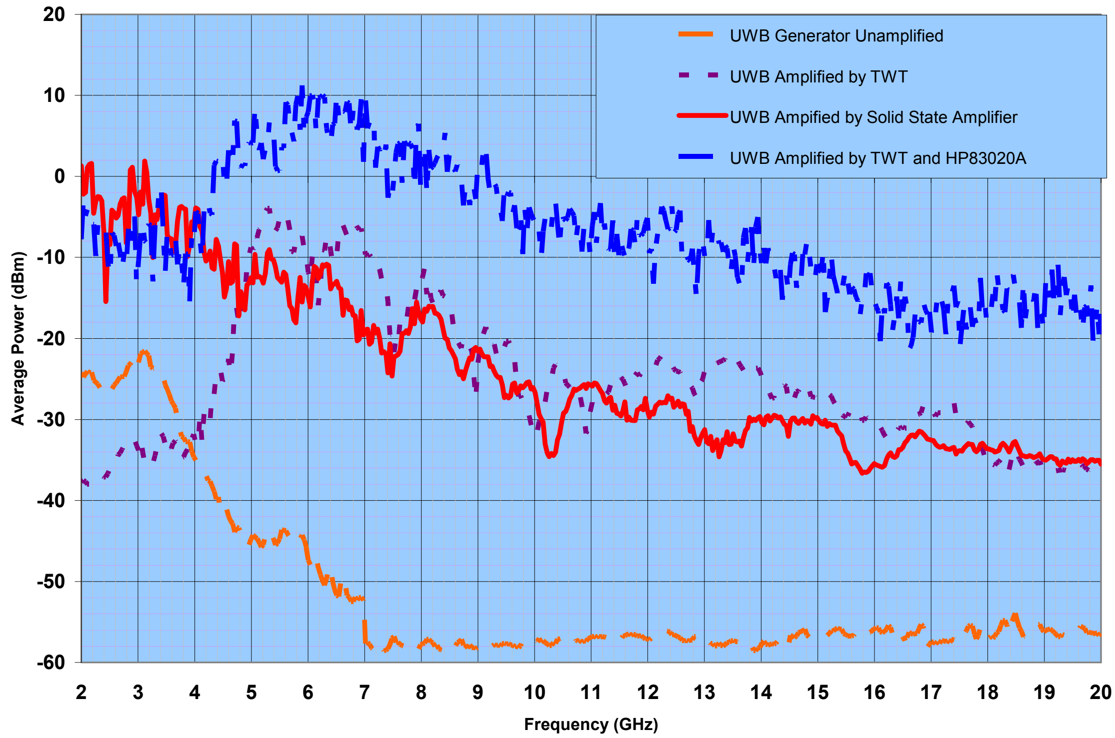

Figure 5 **Spectra of Unamplified UWB, UWB Amplified by Solid State Amplifier, EW TWTA, and Both.**

OVERVIEW OF THE TEST PLAN

The generic test plan for UWB units under test (UUTs) is laid out in the *TEST MASTER PLAN FOR THE NETEX PROGRAM,*[6] hereinafter called the Test Master Plan (TMP). The TMP provides for a progressive suite of tests, each of which builds on preceding tests. The initial test for each unit under test (UUT), is a standard system sensitivity test, based on the published UUT system sensitivity requirements (SSR), such as minimum detectible signal (MDS), *n* dB signal to interference plus additive noise (SINAD), where *n* is specified in system documentation, bit error rate (BER) equal to or greater than some predetermined number, *m*, or some other mutually agreed upon system sensitivity specification (SSS). This SSR then became the interference criterion for all subsequent tests on that UUT.

For all tests described below, the interference threshold was determined in a two (2) step process:

(1) The injected signal was increased until it met the receiver SSR. This level was termed the acquisition threshold (AT).
(2) The injected signal was decreased until it no longer met the receiver SSR. This level was termed the upset threshold (UT).

In most cases, the difference between a receiver's AT and its UT is only one (1) or two (2) dB; however, for some receivers, this difference can be in excess of 10 dB. Each test described below was conducted at each test frequency for the specific UUT except for frequency hopping (FH) systems which were not capable of operating on single frequencies. All FH systems were tested in FH mode as well as any applicable fixed frequency modes. For non-FH systems which have the capability to be tuned, the UUT was tested at three (3) frequencies across its frequency band: a frequency within the bottom 10% of the tuning band, a frequency within the middle 10%, and a frequency within the top 10%.

To test for system sensitivity, a system desired signal, generated by the system receiver test set or some other standard signal source for the particular UUT was injected into the receiver at a high level to establish a high quality system link. The test signal was then reduced until the UUT SSR was no longer achieved, UT, and the input signal level was measured or computed, and recorded for future reference. The desired signal was then increased until the UUT SSR was achieved, AT, and the input signal level was measured or computed, and recorded for future reference. In order to remove system noise from future susceptibility tests, all subsequent tests were conducted at an injected signal level 6 dB greater than AT or more.

Following the system sensitivity test, the UUT was tested for susceptibility to white noise in the UUT's receiver radio frequency (RF) passband/bandwidth. For purposes of these tests, the receiver RF bandwidth (RBW) was determined to be the bandwidth of the most narrow RF or intermediate frequency (IF) bandpass filter in the receiver chain. More narrow system level filters in the receiver's audio or video processing were not considered. Broadband white gaussian noise (BWGN) was injected into the UUT receiver together with the desired signal at system sensitivity plus 6 dB (AT + 6 dB). When the received signal no longer met the established UUT SSR, the BWGN level was measured, recorded, and this level was declared to be the UUT white noise upset threshold (WNUT). The interference to desired signal ratio (I/S) in dB was then determined by calculating WNUT – AT + 6 dB = WNUT I/S. The BWGN level was then increased several dB beyond WNUT and then slowly reduced until the received signal again met the established UUT SSR. The BWGN level was measured, recorded, and this level was declared to be the UUT white noise reacquisition threshold (WNRT). The interference to desired signal ratio (I/S) in dB was then determined by calculating WNRT – AT + 6 dB = WNRT I/S. The results of these tests gave an indication of the effect of additive white noise on the UUT's ability to acquire and hold a low level signal. The results of these were used a metric for the similar performance of the UWB waveforms.

If both the desired signal generator had at least 20 dB of margin between the AT + 6 dB level and its peak output level and the BWGN generator had at least 20 dB of margin between the WNUT level and its peak output level, the TMP provides for a high level BWGN interference test. For this test, the BWGN level was increased to the WNUT + 20 dB and the procedures for the receiver sensitivity test were repeated. The desired signal was then increased until the UUT SSR was achieved for the high level BWGN, HLAT, and the input signal level was measured or computed, and recorded. The HLAT

I/S in dB was then determined by calculating WNUT + 20 - HLAT = HLAT I/S. The desired signal was then reduced until the UUT SSR was no longer achieved, HLUT, and the input signal level was measured or computed, and recorded. The HLUT I/S in dB was then determined by calculating WNUT + 20 - HLUT = HLUT I/S.

The TMP describes a set of ten (10) UWB pulse waveforms, seven (7) generic waveforms and three (3) specific waveforms, to be used against each mode of the victim units at each test frequency; however, the specific waveforms were subsequently deleted, leaving only the generic waveforms. Each test waveform (TW) is described below and in abbreviated form in Table 1:

TW1 – The PRF should be the maximum value available from the pulse generator that results in the fundamental or a harmonic of the PRF falling within the receiver RF passband, as close as possible to the actual receiver tuned frequency, the test frequency (TF). For TFs above 100 MHz, the PRF was determined by dividing the TF by the smallest integer (n) which would yield a value less than or equal to 100 MHz. Thus the PRF = TF/n. For TFs at or below 100 MHz, n was 1. TW1 was not modulated.

TW2 – The base PRF of TW2 was similar to TW1 except that TW2 was dithered in a manner to attempt to partially fill the receiver passband. Since the UWB does not dither any PRFs greater than 80 Mpps, TW2 must be equal to or less than 80 Mpps. Therefore the TW2 PRF was determined by dividing the TF by the smallest integer (m, $m \geq n$) which would yield a value less than or equal to 80 MHz. Thus the PRF = TF/m. For TFs at or below 80 MHz, m was 1. TW2 was dithered by the largest available percentage which would not cause the occupied bandwidth of the dithered signal to exceed the RBW, or if all available dither percentages resulted in an excessive dither bandwidth, the lowest available dither percentage was used.

TW3 – The base PRF of TW3 was the victim RBW. TW3 was dithered by the largest available percentage which would not cause the occupied bandwidth of the dithered signal to exceed the RBW, or if all available dither percentages resulted in an excessive dither bandwidth, the lowest available dither percentage was used.

TW4 – The base PRF of TW4 was the victim RBW. The TW4 modulation was selected on a case-by-case basis to try to cause the most interference to the victim receiver based on the testers' knowledge of the receiver's performance. Altogether, only three (3) different modulations were used: (1) an externally generated swept frequency modulated (FM) PRF at the victim RBW with a deviation of 1 Hz and a rate of 1 kHz; (2) an internally generated OOK with a symbol rate equal to the victim RBW using PN Factor 1, a continuous stream of alternating 1s and 0s; or (3) an internally generated OOK with a symbol rate equal to the victim RBW using PN Factor 12, a true pseudorandom noise-like stream of 1s and 0s.

TW5 – The base PRF of TW5 was the victim RBW/10. TW5 was not modulated.

TW6 – The base PRF of TW6 was the victim RBW*10. TW5 was not modulated.

TW7 – The base PRF of TW7 was the victim RBW/100. TW7 was not modulated.

Table 1 Descriptions of UWB Test Waveforms

Test Waveform (TW)	Pulse Repetition Frequency (PRF)	Modulation of PRF
1	Test Frequency (TF)/n	Not Applicable (N/A)
2	TF/m ($m \geq n$)	Dithered at greatest available percentage (%) which was less than the full receiver RBW.
3	RBW	Dithered to fill all or a portion of RBW
4	RBW	Modulation designed to cause maximum interference to selected victim
5	RBW/10	N/A
6	RBW*10	N/A
7	RBW/100	N/A

Following the BWGN tests, the UUT was tested for susceptibility to each of the UWB test waveforms in the UUT's receiver RF passband. The UWB TW was injected into the UUT receiver together with the desired signal at AT + 6 dB. When the received signal no longer met the established UUT SSR, the UWB level was measured, recorded, and this level was declared to be the UUT UWB upset threshold (UWBUT). The UWBUT I/S in dB was then determined by calculating UWBUT – AT + 6 dB = UWBUT I/S. The UWB level was then increased several dB beyond UWBUT and then slowly reduced until the received signal again met the established UUT SSR. The UWB level was measured recorded, and this level was declared to be the UUT UWB reacquisition threshold (UWBRT). The results of these tests gave an indication of the effect of additive UWB interference on the UUT's ability to acquire and hold a low level signal. The results of these were compared to the WNUT and the WNRT respectively. The UWBRT I/S in dB was then determined by calculating UWBRT – AT + 6 dB = UWBRT I/S.

If both the desired signal generator had at least 20 dB of margin between the AT + 6 dB level and its peak output level and the UWB generator had at least 20 dB of margin between the UWBRT level and its peak output level, the TMP provides for a high level UWB interference test. For this test, the UWB Interference level was increased to the UWBRT + 20 dB and the procedures for the receiver sensitivity test were repeated. The desired signal was then increased until the UUT SSR was achieved for the high level UWB, HLAT(U), and the input signal level was measured or computed, and recorded. The HLAT(U) I/S in dB was then determined by calculating UWBRT + 20 – HLAT(U) = HLAT(U) I/S. The desired signal was then increased until the UUT SSR was achieved for the high level UWB interference level, HLAT, and the input signal level was measured or computed, and recorded. The desired signal was then reduced until the UUT SSR was no longer achieved, HLUT(U), and the input signal level was measured or computed, and recorded. The HLUT(U) I/S in dB was then determined by calculating UWBRT + 20 – HLUT(U) = HLUT(U) I/S.

SUMMARY OF PRELIMINARY RESULTS

Altogether fifteen (15) different receivers, operating in a total of thirty-two (32) modes and at a total of fifty-nine (59) frequencies spanning frequencies from 30 MHz to 16 GHz, were tested. Altogether over 1,000 individual tests were conducted over a period of five (5) months. Receivers tested included communications, aircraft guidance systems, and radars. Although testing has been completed at the time this paper was written, data reduction and results analysis for many of the individual systems tested is still in process. Therefore, much of the composite analysis is also incomplete. However, enough of the analysis has been completed to allow several preliminary observations to be developed. These observations include types of UWB waveforms which probably would or would not cause interference to an UUT, UWB signal strength necessary to cause interference to an UUT, comparison of UWB interference necessary to cause interference to BWGN, and the interference margin (IM) of a UUT for a particular UWB TW.

What UWB Waveforms Do and Do Not Cause Interference?

The initial answer to the above question is that all waveforms tested caused interference to at least some of the UUTs. However, certain waveforms are less likely to cause interference than others. Two very general answers are:

(1) High PRFs cause interference at the frequencies of their spectral lines, but there a significant amount of spectral space between the lines where there is very little or no interference. As an example consider a system operating in a band of 490 – 510 MHz with 1 MHz channel spacing and 1 MHz RBW and an UWB system operating in the vicinity of 500 MHz with a steady PRF of 10 Mpps. An examination of Figure 4 indicates that three (3) channels of the twenty-one (21) available, those at 490 MHz, 500 MHz, and 510 MHz, have a high probability of interference. Interference on the four (4) adjacent channels is 20 dB less likely, and interference at 495 MHz and 505 MHz is about 28 dB less likely. This leaves thirteen (13) interference free channels and six (6) channels with a low probability of interference. If the PRF were higher, the probability of interference in the band would be reduced even more.

(2) Very low PRFs are very unlikely to cause interference at any frequency. For purposes of this report, very low PRF is considered to be any PRF equal to or less than RBW/100. Our present data indicates that such PRFs are only capable of causing interference to the UUT about one third (⅓) of the time. In receivers which respond to average power, even a very strong signal which is only present 1% of the time or less is not capable of causing much

interference, even when the desired signal strength just barely exceeds the SSR. Error correction coding reduces the probability of interference even more. Receivers which respond to peak signals are more susceptible to interference from low PRF UWBs, but even these can benefit from interference cancellation techniques.

Other waveform generation and frequency management techniques are also available to help reduce the probability of the occurrence of interference to legacy receivers which may be operating in the vicinity of a UWB system.

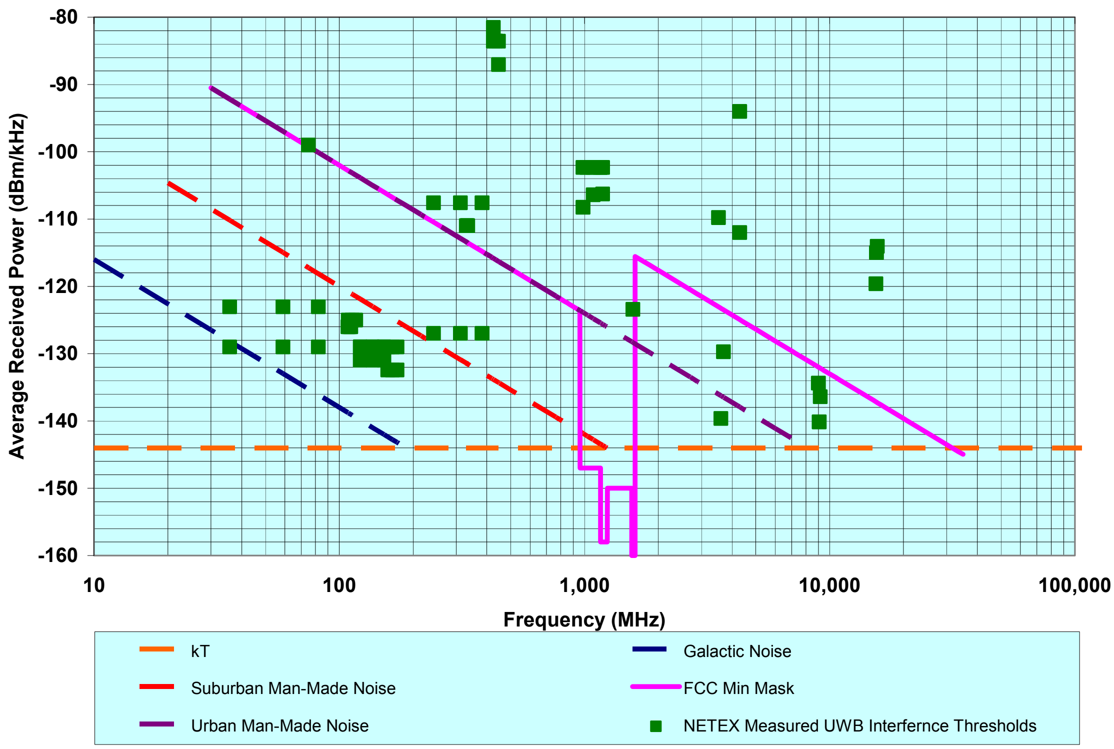

Figure 6 **Comparison of Onset of UWB Interference to Thermal and Background Noise and the FCC Mask**

At What Level Does an UWB Source Cause Interference?

There is no easy answer to this. There are just too many variables for a general answer.

Figure 6 shows the average power level, adjusted for a 1 kHz RBW, for the onset of UWB interference for each of a selected set of UUTs, for each mode and each test frequency. As a reference for the significance of these onset levels, Figure 6 also provides lines indicating the room temperature thermal background (kT, -144 dBm/kHz), galactic background noise, suburban and urban noise backgrounds,[7] and the FCC mask shown in Figure 1. The FCC mask in Figure 1 has been adjusted in Figure 6 to indicate the average power at the input to an isotropic transmit antenna. What this chart shows is that many legacy military systems are susceptible to UWB interference at levels well below those allowed by the FCC, but significantly above the noise levels expected in rural areas.

How Does UWB Interference Compare to Broadband Noise Interference?

In our discussion of the test plan above, we listed a set of tests to determine the interference potential from BWGN. The reason for these tests was to provide a metric against which to measure UWB interference. In many modern systems, white noise is considered to be the worst possible interference source and it has become the metric against which other interference sources are compared. Figure 7 shows a comparison of the interference potential of each of the TWs at each test frequency for a selected set of the UUTs. In this chart, a positive value indicates that UWB interference begins at a higher power level than BWGN interference; a negative number indicates that UWB interference begins at a lower power level than does BWGN interference.

The bottom line from the data in Figure 7 is that there is no good generalization to be made about the probability of UWB interference as compared to white noise. The reader will note that at many of the test frequencies, there are UWB TWs above the 0 dB line and UWB TWs below it. This indicates that significant knowledge of the potential interference victim is needed in order to develop a non-interfering waveform.

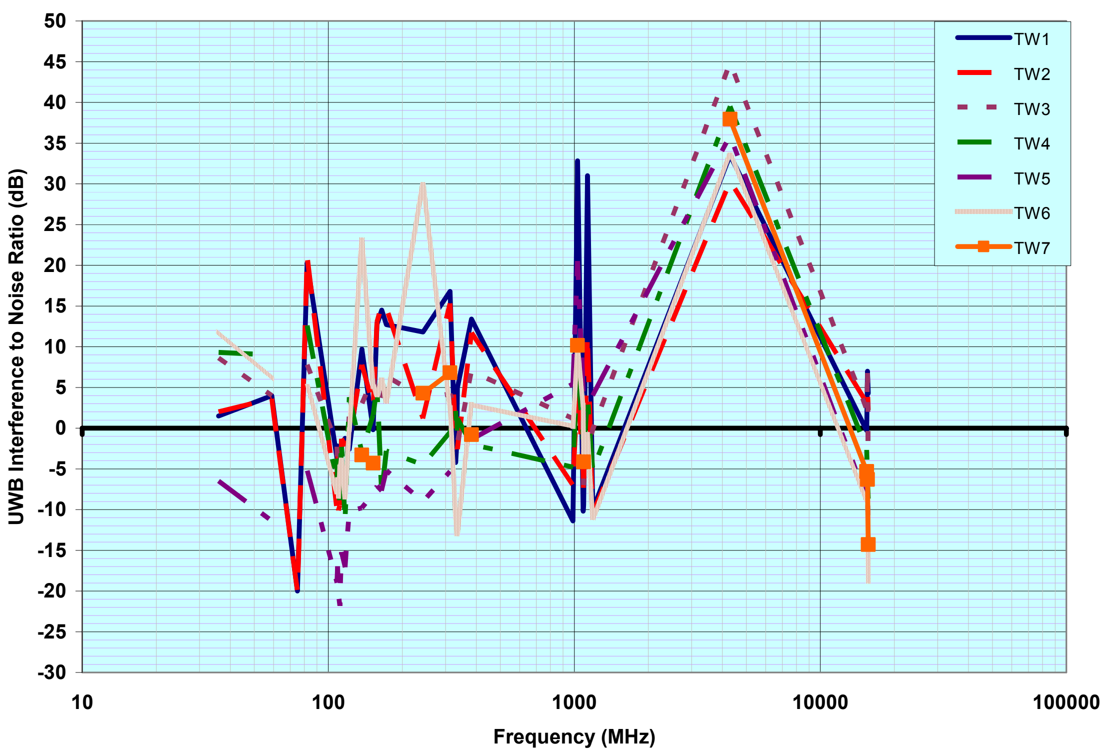

Figure 7 **Comparison of Onset of UWB Interference to Onset of Noise Interference for the Interference Victim**

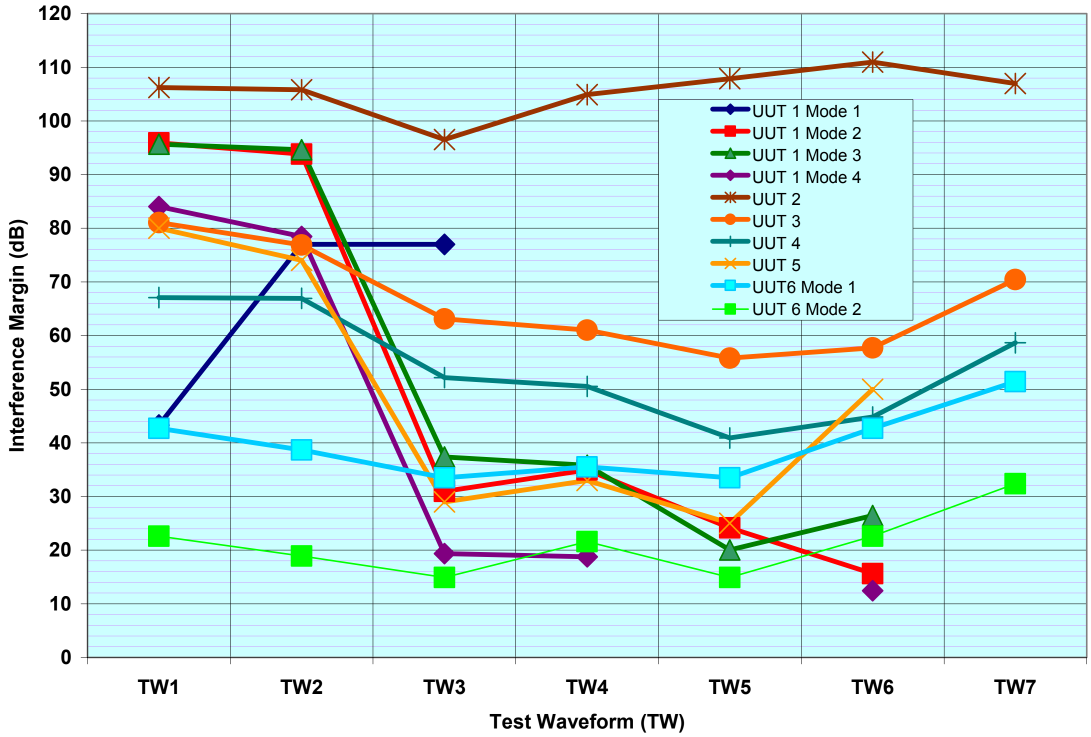

Figure 8 Interference Margin for Selected Interference Victims

How Much Interference Margin (IM) Does an UWB Source Have?

The IM of a potential interference source is the amount of attenuation required in the interference source path to prevent interference to the potential victim. Thus the larger the IM the more potential the source has to cause interference to a particular potential victim. The IM is a very case specific metric.

Figure 8 provides the UWB IMs for six different UUTs operating in ten (10) different modes versus each of the UWB TWs. If there is no entry for a UUT in a specific TW column, either the UUT was not tested for that TW or the specific UWB TW was unable to cause interference in the UUT. Considering the spread for all the IMs, it is very difficult to draw any conclusions at this time.

WHERE DO WE GO FROM HERE?

On 4 March, the NETEX Program presented its Go/No Go briefing to the Director of DARPA. As a result of that briefing, NETEX was authorized to proceed onto the next phase, tasks 2 and 3, of the program.

Phase 2 – Tasks 2 and 3 encompass the development of networked UWB system(s). The objective of Task 2 is to develop an improved UWB physical layer that will result in small, reliable, deployable and affordable radios for military networks. To meet the objective of Task 2, it will be necessary to push the UWB physical layer to the point where it is capable of reliably supporting advanced low probability of detection (LPD) ranging, location and networking protocols.

The Task 2 effort should integrate the lessons learned from the testing modeling and simulation conducted during Phase 1 to develop UWB systems that can coexist with legacy systems and intentional jammers. The UWB waveform for Task 2 will be implemented in the design space identified in Phase 1 (i.e., the spectral mask developed during Phase 1 will be used in Task 2 to decide the location in the spectrum, bandwidth, data rate and power limitations to implement a UWB sensor and communications network that will not cause interference to in band legacy receivers).

The major development efforts required for Task 2 are improved detection, modulation and coding to achieve 10 dB to 30 dB enhancement in system performance, interference excision techniques, simultaneous multi-function (comm., radar, timing and location), and an order of magnitude reduction in size and power. UWB systems developed during Phase 2 should achieve 10^{-3} uncorrected bit-error rate (BER) with multiple (minimum of three) in band interferes located within 20 meters distance from the UWB system. The interferes should have modulation, bandwidth and effective radiated power that is representative of legacy systems operating in the band of interest, and they should not cause interference to the UWB system when all systems are operating.

The objective of Phase 2, Task 3, will be the development of algorithms, protocols and distributed control for robust, scalable ad-hoc networking. The result will be a precision time based ad-hoc network that is capable of self organization and robustness using software adaptation. The network will also provide modular design and open interfaces for "inter-stack" awareness and will provide a capability of simultaneous timing, location, ranging and communications. This will enable a new allocation of functions and different control of the network than is currently seen with the standard OSI model. The networking capabilities should be demonstrated for a multi-node UWB mobile ad-hoc network and it should be extensible to a density of 100 to greater than 10,000 nodes in an area that is1 km^2.

Examples of UWB systems that are of interest are identified below.

1. Handheld UWB communications network. A handheld device is needed to enable and support mobile, ad-hoc network applications in a tactical environment. At a minimum, the system should be able to support voice and data communications at 10 kb/s at a range of up to 500 meters. The system should consider unique approaches to the networking protocols that enable simultaneous transmissions by networked systems without causing interference to legacy systems and allow the UWB receiver to operate within 20 meters of a minimum of three in band legacy transmitters without experiencing interference (the UWB system should be capable of achieving a 10^{-3} uncorrected BER). The life required of the UWB system is 2 days. The system should be demonstrated for a network consisting of 20 nodes and should be extensible to more than 10,000 nodes in a 1 km^2.

2. Ground-based UWB sensor network. A high data rate short range communication system is required for transmitting video and other information in a tactical environment. The system should provide data communications at 10 Mb/s with a range of 100 meters. The UWB system, when transmitting should not cause interference to in band legacy receivers and the UWB receiver should be capable of achieving a 10^{-3} uncorrected BER when operating within 20 meters of a minimum of three in band legacy transmitters. The life required for the system is 30 days and the system should be demonstrated for a network consisting of 50 nodes and should be extensible to more than 10,000 nodes in 1 km^2.

3. Radar Sensor. A radar sensor is required for high resolution imaging requiring foliage or wall penetration and other applications. The radar should be able to detect a 1 m^2 target at a range of 500 meters. The radar when transmitting should not cause problems to in band legacy receivers and the UWB receiver should be capable of achieving a probability of detection to be determined (TBD) and a probability of false alarm TBD when operating within 20 meters of a minimum of three in band legacy systems. The life requirement for the radar system is 30 days and the system should be demonstrated for a network consisting of 50 nodes and should be extensible to more than 10,000 nodes in 1 km^2.

REFERENCES

[1] MIL-STD-462, MILITARY STANDARD MEASUREMENT OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS

[2] MIL-STD-462D, MILITARY STANDARD MEASUREMENT OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, 13 January 1993.

[3] MIL-STD-461E, MILITARY STANDARD REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE EMISSIONS AND SUSCEPTIBILITY

[4] Federal Communications Commission, *Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems*, ET Docket 98-153, First Report and Order, adopted 14 February 2002, released 22 April 2002.

[5] 47CFR15, *Radio Frequency Devices*, released 25 April 2002; http://www.fcc.gov/oet/info/rules/part15/part15_4_25_02.pdf.

[6] **The Defense Advanced Research Projects Agency (DARPA) Networking in Extreme Environments (NETEX) Program, *TEST MASTER PLAN FOR THE NETEX PROGRAM*, unpublished.**

[7] CCIR Report 322, *World Distribution and Characteristics of Atmospheric Radio Noise*, 10th Plenary Assembly, Geneva; 1963